Models and Modelling in STEM Education: Nature, Roles, and Implementation

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Abstract
This chapter elaborates the key aspects of the nature, roles, and implementation of models and modelling in STEM education. Regarding nature, although models and modelling differ between the STEM subjects there are alsosimilarities, for example, concerning visual models and representations. The roles of models in the STEM subjects are dominated by conceptual models, while in technology/engineering manipulation of physical models is also important. Furthermore, common to all STEM subjects is the construction, evaluation, revision and (re-)use of models. Concerning the implementation of models and modelling in STEM education, evidence points to the relevance of including modelling in authentic engineering activities.

Keywords
Models; modelling; representations; STEM education; STEM literacy

1. Introduction

In a 2019 commentary, we reinforced the argument that models and modelling could serve as a bridge between the STEM subjects in educational practice (Hallström & Schönborn, 2019). This synthesis emphasised that models and modelling are central to fostering authentic STEM education. The subjects of science, technology, engineering and mathematics are often subsumed into the notion of 'STEM', an acronym used particularly in the last two decades to define content, craft curricular goals, define educational policy and/or motivate political agendas. However, a precise interpretation and operational definition of STEM remains elusive (Breiner et al., 2012) with various camps of scholars suggesting that it is often used in far too general or in far too specific terms (e.g. Henderson et al., 2017; Tang & Williams, 2019). Another saliently discussed attribute is the relative contribution of each 'S', 'T', 'E' and 'M' subject to the overall STEM construct, with contemporary developments also advocating the inclusion of an 'A' for artistic subjects (STEAM), and 'i' for information technologies (iSTEAM). Such discussion calls for further and clearer considerations of the nature, roles and implementation of STEM, and how the subjects can be meaningfully linked. In this regard, models and modelling act as point of departure for linking the STEM subjects, thereby contributing to the discussion of the meaning, integration and application of STEM education.

Models and modelling are crucial for solving problems, making predictions, and communicating concepts and constructs (e.g. Müller, 2009; Vincenti, 1990). Models clarify aspects of reality and range from simple conceptual diagrams and early prototypes to advanced mathematical models and machine learning algorithms. Therefore, the competencies needed to create, use, apply, evaluate and revise models are necessary for gaining an in-depth understanding of scientific practice, technological and engineering design, and mathematical tools (Schwarz et al. 2009).

In this chapter we elaborate upon the nature, roles, and implementation of models and modelling in STEM education, by posing the following questions:

- What is the nature of models and how are they represented?
- What are the roles of models in relation to specific modelling processes, knowledge and skills?
- How can models and modelling be implemented in STEM education?

In pursuit of implementing models and modelling across the four STEM disciplines, the relationship between the nature, roles and implementation of models should be seen as being both intertwined as well as informing one another. The following sections unpack these three key aspects of models and modelling in STEM education by responding to each of the questions that frame the chapter.

2. The nature of models and their representation

According to Gilbert et al. (2000), models are *ubiquitous representations of phenomena* such as objects, ideas, concepts, systems, events, and processes. Models describe, explain, construct, and predict phenomena by organising relevant information, generating hypotheses, and explaining how information may be related (Brady et al., 2015; Lesh et al., 1997; Lesh et al., 2013). In doing so, models communicate a simplified version of reality through concrete, conceptual, and formal/symbolic depictions (de Vries, 2013). In this regard, models portray entities in smaller (e.g. a spaceship blueprint) or larger (e.g. a coronavirus diagram) visual forms than the actual represented phenomenon, as abstractions (e.g. force field arrows), or as depictions of concrete and abstract entities (e.g. augmented predicted visual path of a photographed projectile) (Gilbert et al. 2000). Furthermore, models represent dynamic systems such as cause-and-effect relationships as well as in coordinated depictions where the system is communicated as more than the 'sum of its parts' (Zawojewski et al., 2008; Diefes-Dux et al., 2008).

Different *modes of representation* are used to communicate a model (Schönborn & Anderson, 2009). Herein, a model can be expressed in at least five different modes of representation, namely concrete (e.g. 3D physical models), verbal (e.g. spoken or written description of model entities); symbolic (e.g. chemical formulae and algorithms), visual (e.g. diagrams and animations), or gestural (e.g. bodily representation of model entities) (Gilbert, 2004). Whilst in science education models are often communicated through concrete, visual, verbal, mathematical, or gestural representations, in technology education models often include iconic (e.g. a sketch), analogue (e.g. simulation), and symbolic (e.g. mathematical) models (Davies & Gilbert, 2003).

Models in science are often central to knowledge building, and fundamental for providing explanations and predictions. Scientific models can comprise consensus models (used in research), which in turn serve to illustrate the nature of science, or historical models (replaced by revised models over time) (Justi & Gilbert, 2002). Nia and de Vries (2017) consider models as “techno-scientific artefacts”. Herein, they have an intrinsic nature, intentional nature, as well as an intrinsic-intentional interconnection. In this regard, Nia and de Vries (2017) have proposed a framework for the “dual nature” (cf. de Vries & Meijers, 2013) of models which may be applied across the STEM subjects. Nia and de Vries (2017) describe the “intrinsic” nature of models as concerning the material structure and form of models, whereas the “intentional” nature of models concerns their purposes or functions, that is, whether they are used for exploration, design or communication. In technology and engineering, knowledge can be developed by constructing and manipulating models, wherein models are used to comprehend design concepts and optimise prototypes (Citrohn & Svensson, 2020; France et al., 2011; France, 2018). In mathematics, a model can be defined as the combination of an extra-mathematical domain, a mathematical domain, and the translation between the two (Niss, 2012).

3. Roles of models in relation to specific modelling processes, knowledge and skills

Justi and Gilbert (2002) have advocated that models and modelling play a central role both in *learning* science and learning how to *do* science. The modelling process includes determining the purpose of the model, which often includes formulating a mental model of the phenomenon, and ascertaining in what mode of representation (e.g. visual, concrete or symbolic) to express the model. Subsequently, while “testing” whether a model satisfies its foreseen purpose, the modeller infers the scope and limitations of the model.

Regarding the specific roles of models for learning science, Gilbert (2004) states that students should understand what a model is; understand the entities that a particular model represents and how these entities interact with each other; mentally visualize models; display visual literacy skills associated with interpreting models; understand analogy and metaphor in relation to describing model components; and, understand how a model can be used. According to Gilbert et al. (2000) modelling can include several different model types with different roles: mental models (cognitive representations); expressed models (available for others to interpret); consensus models (expressed models that gain acceptance); scientific models (tested expressed models that become predictive tools); historical models (exist in a context and perhaps later displaced); curricular models (historical models in curricula); teaching models (aid interpreting historical and curricular models); and, hybrid models (coordinate scientific, historical or curricular models).

It follows that two roles of modelling in science and design & technology education are modelling ideas in the mind – communicating with oneself – and modelling ideas in the world – communicating with others. The modelling process includes having experience of the phenomenon or problem; formulating suitable metaphors and analogies to express the model; visualizing the outcome of the modelling process; producing a representation of the model, and, evaluating the scope and limitations of the produced model (Davies & Gilbert, 2003).

In technology and engineering education, models support development of theories and artefacts through manipulation (e.g. concrete models) and mental exploration (e.g. conceptual models, sketches). Furthermore, the intrinsic and intentional nature of models in technology and engineering can support building, revising, and communicating knowledge and artefacts related to pedagogical use (e.g. educational models); procedural use (e.g. computer-aided design); and, decisional use (e.g. climate change models). The intrinsic-intentional interrelation of models informs design (designers' and users' points of view); simplification (abstraction and idealization); iterativity (trial and error); and, adequacy (judging appropriateness and effectiveness) (Nia & de Vries, 2017; de Vries, 2013). Another aspect of modelling in technology and engineering education is functional modelling, which concerns the development of a design concept and prototyping of the realised outcome, often as an artefact/system. Technological modelling thus provides epistemic strategies for reinforcing that the technological outcome is "fit for purpose"; the purpose is a designed intervention where the outcome is judged by a successful function (France et al., 2011; France, 2018).

In engineering education modelling processes are often similar to that of technology education, but principles from mathematics education for so-called model-eliciting activities (MEAs) may also include model construction, reality, self-assessment, model documentation, model shareability and re-usability, and production of an effective prototype (Zawojewski et al., 2008; Diefes-Dux et al., 2008). Model-eliciting activities (MEAs) in mathematics and engineering education thus include posing the following questions: is the situation authentic? (the reality principle); is the construction or modification of a model required? (the model construction principle); are there clear criteria for assessing the usefulness of the model? (the self-evaluation principle); does the model apply to multiple situations? (the model generalization principle); and, will the solution provide a useful prototype for interpreting other similar situations? (the simple prototype principle) (Brady et al., 2015; Lesh et al., 1997; Lesh et al., 2013).

4. Implementation of models and modelling in STEM education

4.1 Strategies for teaching models and modelling in STEM education

To promote a model-based teaching approach, science and technology educators need to communicate to learners what representational components make up a model, demonstrate the scope and limitations of different models, adapt model usage depending on the content taught, and, design meaningful activities that include learners' active model construction (Gilbert, 2004). Justi and Gilbert (2002) suggest the following modelling strategies during teaching: communicate the purpose of a particular modelling activity; provide an authentic experience of the phenomenon being modelled during any practical work; specify the model source; support the mental imagery of a particular model; and, show relationships between different modes of representation of the model (cf. Davies & Gilbert, 2003). It follows that modelling in science and technology involves both a developmental cycle where iterative changes are associated with the produced model, a "fitness for purpose" where a certain specification is envisioned, as well as, a visualization of the intended outcome of the process. For Gilbert et al. (2000), teaching models and modelling contributes to learning because mental modelling is central to understanding. Moreover, expressing and testing models also reflect the 'doing' of science, and understanding science relies on interpreting scientific and historical models.

According to de Vries (2013), fusing modelling and design activities enhances STEM learning since design connects scientific, technological, engineering and mathematical components. In addition, modelling activities provide a bridge between a practical scenario and required mathematical analytical tools to model different aspects of reality. In particular, this is the case in problems when understanding reality (science) and manipulating reality (technology and engineering) are foreseen. Developing students' conceptual understanding of modelling and their intrinsic-intentional perspective of models, can foster an enhanced individual modelling ability. In this way modelling can be used as a pedagogical strategy to support STEM learning (France et al., 2011; France, 2018; Nia & de Vries, 2017).

Effective teaching of models and modelling requires paying concerted attention to the design of activities, with adequate time for the activities to be realised (Niss, 2012). In mathematics, students should be provided with an opportunity to experience how mathematical models come to be, and interrogate the trade-offs involved in developing a mathematical model, including assessing the limitations and strengths of different models. When students engage in model-eliciting activities to assess and monitor their own work using authentic tools, they induce the construction, modification, and refinement of powerful conceptual models. Overall, modelling abilities in STEM can be developed along various dimensions that include: from concrete to abstract, from specific to general, from local/refined to global, or from intuitions to formalisations (Brady et al., 2015; Lesh et al., 1997; Lesh et al., 2013; Zawojewski et al., 2008; Diefes-Dux et al., 2008).

4.2 Integration of models and modelling in STEM curricula and practice

According to Gilbert (2004), integrating models and modelling can increase the authenticity of STEM curricula by explicitly training science teachers in the nature and role of models. Integrating models and modelling in STEM curricula can be promoted through pupils learning to use models, revise models, reconstruct models, and construct models *de novo*. Pre- (and in-) service STEM education should also focus heavily on unpacking the nature of a 'model' and how to use different models in different contexts (transfer). This can be promotedby following the historical sequence of model development in a certain topic area as a means of cognitive reconstruction in modelling, and, providing skills for evaluating the strengths and limitations of models (Justi & Gilbert, 2002).

Furthermore, implementing models and modelling to embrace STEM education requires considering the importance of the learning context - curricula need to be enterprising, effective, of good quality and personally relevant (Margot & Kettler, 2019). Such curricula will allow learners to perceive relationships between science and technology content while applying knowledge in real-world problem solving (Davies & Gilbert, 2003). Models and modelling should therefore be viewed by educators and curriculum developers as a valuable bridge between science, technology, engineering and mathematics, which in turn, may promote authentic STEM education. Furthermore, there must be opportunities for students to develop activities to find solutions to, and make informed decisions about real-world issues by integrating both science and technology concepts (Gilbert et al., 2000).

For de Vries (2013), the encompassing facets of modelling allow it to be integrated at various points of student development in STEM curricula. Primary students could, for example, be provided with early experiences of modelling through concrete models, whereas secondary students could engage with formal aspects of modelling, which include nature, types and functions of models and modelling. The intrinsic, intentional and intrinsic-intentional perspective of models can, according to Nia and de Vries (2017), be used to analyse curricula and policy documents on the integration of models and modelling. These perspectives are a potential benchmark of what a curriculum should contain with respect to models and modelling in the STEM subjects. Moreover, modelling can support the development of an understanding of the nature of technology and the nature of science both as separate domains, but also in relationship with one other as well as engineering and mathematics (France et al., 2011; France, 2018).

According to Niss (2012), teaching about modelling should be used to support students' concept formation and sense-making in mathematics, especially when it comes to the transfer to authentic problems. Thus, modelling requires students to actively engage multiple skills (Niss, 2012). Implementing models and modelling in authentic learning programmes can help students construct, modify and refine conceptual models that are applicable not only to mathematics but also to other modelling adaptation activities in engineering, technology and science (Brady et al., 2015; Lesh et al., 1997; Lesh et al., 2013). In this way, students are potentially better positioned to understand the strengths and weaknesses of a conventional model, and better prepared to apply, adapt, and even create new models for novel and similar situations, across the STEM subjects (Zawojewski et al., 2008; Diefes-Dux et al., 2008; Kertil & Gurel, 2016).

5. Conclusions and Implications for STEM Education

This chapter has elaborated upon the nature, roles, and implementation of models and modelling in STEM education. Regarding the nature of modelling, although models and modelling differ slightly between the STEM subjects there are some clear similarities, for example, concerning visual models and representations (e.g. Tang & Williams, 2019). Exploring these similarities and bringing differences to light could strengthen STEM education and STEM literacy. Modelling is often about representing simplified versions of reality that take on concrete/physical, conceptual, verbal, gestural or symbolic/mathematical forms (Gilbert, 2004). Models are therefore representations of ideas, objects, systems, events, or processes which are central in the STEM disciplines. At a conceptual level, models are even systems of description in themselves; for explaining, constructing, modifying, manipulating and/or predicting a complex series of experiences. Models thereby help to organize relevant information so as to generate or (re)interpret hypotheses about given situations, designs or processes, or explain how information is related, something which is at the core of all the STEM subjects.

Given the above, we must also be cognisant of the influence of the rapidly developing digital landscape on models and modelling in STEM education. Notably, artificial intelligence (AI), neural networks and machine learning are changing the way models are designed and how modelling is carried out, because some of the modelling is now done not by humans but by computers (Campbell, 2020; Carr, 2015; Wiberg et al., 2019), which are also "learning" to be more proficient modellers. Furthermore, models are increasingly becoming digital and mathematical in conjunction with more complex technological systems, which will also have repercussions on the field of STEM education; if machines learn to model increasingly complex systems, humans may become less involved in, or even lose some of the control over, STEM projects (cf. Hallström, 2020).

When it comes to the roles of models and modelling in STEM education, models support design of artefacts and theory development through manipulation (e.g. concrete models) or mental exploration (e.g. conceptual models, sketches) (de Vries, 2013), and, in the latter case, modelling ideas in the mind for communicating with oneself and modelling ideas in the world for communicating with others (Davies & Gilbert, 2003). Some of the primary skills associated with modelling include:understanding what a model is and how to use it; carefully defining the context of the modelling process; mentally visualizing a model outcome; deciding what mode of representation to express the model; and understanding how a model can be constructed, interpreted, evaluated and revised. A critical ability is also being able to assess the strengths and limitations of a particular model (Schönborn & Anderson, 2009).

Concerning the implementation of models and modelling in STEM education, a lot of evidence points to the relevance of including modelling in authentic engineering design projects. In such engineering projects students will formulate scientific and mathematical models and algorithms to optimise their designs, which are tested with engineering prototypes and functional models. Hence, new knowledge is developed not only about science, mathematics and technology but also about the engineering design process itself; students are required to apply existing knowledge about, for instance, modelling previously learnt in science, technology and/or mathematics (Ammon, 2017; de Vries, 2018; Hallström & Ankiewicz, 2019; Kertil & Gurel, 2016).

Modelling is an indispensable feature of STEM education (see e.g., Banks and Barlex, 2014; Gilbert, 2004; Williams, 2017). Recent studies show that there are advantages in teaching and learning modelling as an integrated STEM literacy. For instance, Krell and Krüger (2017) have shown that STEM students have more advanced “meta-modelling knowledge” than students of other, single disciplines at the tertiary level. Additionally, models and modelling are often seen as a “language” of pursuing an integrative STEM literacy (e.g. Kertil & Gurel, 2016). Albeit so, further research is needed to ascertain how modelling can be developed to purposefully and systematically interconnect the STEM subjects.

In conclusion, this chapter emphasizes that modelling activities can serve as an important path toward authentic STEM education (e.g. France, 2018; Gilbert et al., 2000). In addition, models and modelling can be used as a vehicle to foster STEM literacy and the transfer of knowledge and skills between STEM subjects (e.g. Niss, 2012). To accomplish this, teaching must take into account modelling frameworks that are based on authentic STEM practices (Breiner et al., 2012). In pursuing this vision, it must be realised that integrating science, technology, engineering and mathematics remains a complex challenge that calls for what Kelley and Knowles (2016) term “a new generation of STEM experts” (p. 1) that can navigate the future expected transitions between the STEM disciplines. Finally, in order to implement and fulfil an integrated STEM literacy, it is crucial that model-based pedagogies intended for STEM education classrooms are empirically investigated and evaluated in real education contexts (Margot & Kettler, 2019).

References

Ammon, S. (2017). Why designing is not experimenting: Design methods, epistemic praxis and strategies of knowledge acquisition in architecture. *Philosophy & Technology, 30*, 495-520.

Banks, F. & Barlex, D. (2014). *Teaching STEM in the secondary school: Helping teachers meet the challenge*. London: Routledge.

Brady, C., Lesh, R., & Sevis, S. (2015). Extending the reach of the models and modelling perspective: A course-sized research site. In G.A. Stillman et al. (Eds.), *Mathematical Modelling in Education Research and Practice* (pp. 55-66). Dordrecht: Springer International Publishing.

Breiner, J. M., Harkness, S. S., Johnson, C. C., & Koehler, C. M. (2012). What is STEM? A discussion about conceptions of STEM in education and partnerships. *School Science and Mathematics, 112*(1), 3-11.

Campbell, M. (2020). Automated Coding: The Quest to Develop Programs That Write Programs. *Computer, 53*(2), 80-82. doi: 10.1109/MC.2019.2957958.

Carr, N. (2015). *The glass cage: How our computers are changing us*. New York: Norton.

Citrohn, B., & Svensson, M. (2020). Technology teacher's perceptions of model functions in technology education. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-020-09632-8

Davies, T. & Gilbert, J. (2003). Modelling: Promoting creativity while forging links between science education and design and technology education. *Canadian Journal of Science, Mathematics and Technology Education, 3*(1), 67-82.

de Vries, M.J. (2013). Modeling in technology and engineering education. In P.J. Williams & D. Gedera (Eds.), *PATT 27, Technology Education for the Future: A Play on Sustainability*, Christchurch, New Zealand, 2-6 December, 2013. Waikato, NZ: University of Waikato.

de Vries, M. J., & Meijers, A. W. M. (2013). Beliefs, acceptances and technological knowledge. In M. J. de Vries, S. O. Hansson, & A. W. M. Meijers (Eds.), *Norms in technology* (pp. 55–65). Dordrecht: Springer.

Diefes-Dux, H.A., Hjalmarson, M.A., Miller, T.K. & Lesh, R. (2008). Model-Eliciting Activities for Engineering Education. In J.S. Zawojewski, H. Diefes-Dux & K. Bowman (Eds.), *Models and Modeling in Engineering Education: Designing Experiences for All Students*. Rotterdam: Sense Publishers.

France, B. (2018). Modeling in Technology Education: A Route to Technological Literacy. In M.J. de Vries (Ed.), *Handbook of Technology Education*. Dordrecht: Springer.

France, B., Compton, V. J., & Gilbert, J. K. (2011). Understanding modelling in technology and science: the potential of stories from the field. *International Journal of Technology and Design Education, 21*(3), 381–394.

Gilbert, J.K., Boulter, C.J. and Elmer, R. (2000). Positioning Models in Science Education and in Design and Technology Education. In Gilbert, J.K. and Boulter, C.J. (Eds.), *Developing Models in Science Education*. Dordrecht: Kluwer Academic Publishers.

Gilbert, J. (2004). Models and modelling: Routes to more authentic science education. *International Journal of Science and Mathematics Education, 2*(2), 115–130.

Hallström, J. (2020). Embodying the past, designing the future: technological determinism reconsidered in technology education. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-020-09600-2

Hallström, J. & Ankiewicz, P. (2019). Laying down the "T" and "E" in STEM education: Design as the basis of an integrated STEM philosophy. In S. Pulé & M.J. de Vries (Eds.), *Proceedings PATT 37: Developing a knowledge economy through technology and engineering education*, 3-6 June 2019 University of Malta, Msida Campus (pp. 187-194). Msida: University of Malta.

Hallström, J., & Schönborn, K.J. (2019). Models and modelling for authentic STEM education: reinforcing the argument. *International Journal of STEM Education* 6, 22. https://doi.org/10.1186/s40594-019-0178-z

Henderson, C., Connolly, M., Dolan, E.L., Finkelstein, N., Franklin, S., Malcom, S., Rasmussen, C., Redd, K. & St. John, K. (2017). Towards the STEM DBER Alliance: why we need a discipline-based STEM education research community. *International Journal of STEM Education, 4*(14), 1-4.

Justi, R.S. & Gilbert, J.K. (2002). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education, 24*(4), 369-387.

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*(1), 11.

Kertil, M., & Gurel, C. (2016). Mathematical modeling: A bridge to STEM education. *International Journal of Education in Mathematics, Science and Technology, 4*(1), 44-55.

Krell, M. & Krüger, D. (2017). University students' meta-modelling knowledge. *Research in Science & Technological Education, 35*(3), 261-273.

Lesh, R., Amit, M., & Schorr, R. Y. (1997). Using "real-life" problems to prompt students to construct conceptual models for statistical reasoning. In *The assessment challenge in statistics education* (pp. 65-83). IOS Press.

Lesh, R., English, L., Sevis, S., & Riggs, C. (2013). Modeling as a means for making powerful ideas accessible to children at an early age. In S.J. Hegedus & J. Roschelle (Eds.), *The SimCalc Vision and Contributions* (pp. 419-436). Dordrecht: Springer.

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: a systematic literature review. *International Journal of STEM Education, 6*(2), 1-16.

Müller, R. (2009). The notion of a model: A historical overview. In A. Meijers (Ed.), *Philosophy of technology and engineering sciences* (pp. 637–664). Burlington, MA: North Holland.

Nia, M. G., & de Vries, M. J. (2017). Models as artefacts of a dual nature: a philosophical contribution to teaching about models designed and used in engineering practice. *International Journal of Technology and Design Education, 27*(4), 627-653.

Niss, M. (2012). Models and modelling in mathematics education. *Ems Newsletter, 86*, 49-52.

Schönborn, K. J., & Anderson, T. R. (2009). A model of factors determining students' ability to interpret external representations in biochemistry. *International Journal of Science Education, 31*(2), 193-232.

Schwarz, C. V. et al. (2009). Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners. *Journal of Research in Science Teaching, 46*(6), 632–654.

Tang, K. S., & Williams, P. J. (2019). STEM literacy or literacies? Examining the empirical basis of these constructs. *Review of Education, 7*(3), 675-697.

Vincenti, W.G. (1990). *What engineers know and how they know it*. Baltimore, Maryland: Johns Hopkins University Press.

Wiberg, A., Persson, J., & Ölvander, J. (2019). Design for additive manufacturing—A review of available design methods and software. *Rapid Prototyping Journal*. https://doi.org/10.1108/RPJ-10-2018-0262.

Williams, J. (2017). The Vocational Goals of STEM Education: Is that Enough? Paper presented at *PATT 2017, Technology & Engineering Education – Fostering the Creativity of Youth Around The Globe*, Philadelphia, PA, 10-14 July 2017.

Zawojewski, J.S., Hjalmarson, M.A., Bowman, K.J. & Lesh, R. (2008). A Modeling Perspective on Learning and Teaching in Engineering Education. In J.S. Zawojewski, H. Diefes-Dux & K. Bowman (Eds.), *Models and Modeling in Engineering Education: Designing Experiences for All Students*. Rotterdam: Sense Publishers.

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